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A study of low-power density laser welding process with evolution of free surface

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Abstract

In this study, numerical investigation has been performed on the evolution of weld pool geometry with moving free surface during low-energy density laser welding process. The free surface elevates near the weld pool edge and descends at the center if $d\sigma/dT$ is dominantly negative. It is shown that the predicted width and depth of the weld pool with moving free surface are a little greater than those with flat weld pool surface. It is also believed that the oscillation of the weld pool surface during the melting process augments the rate of convective heat transfer in the weld pool. The present analysis with moving free surface should be considered when Peclet number is greater and Weber number is much smaller than one since the deformation of the weld pool surface is noticeable as Pe number increases and We number decreases, especially when $\sqrt{Pe}/We$ is greater than the order of 10.

Keywords: Laser welding; Free surface flow; Marangoni convection; Continuum surface force

1. Introduction

Lasers are very efficient means in performing precise industrial welding process, because they have a number of attractive features such as high welding strength, high welding speed, and minimal heat-affected region than TIG(tungsten inert gas) welding, CO_2 welding, and other welding processes. Incident laser beam is partially reflected off the target surface, and the remains are absorbed by the target material, which consequently raises the temperature of the target surface above melting point. According to the power density of the incident laser beam, laser welding process is generally divided into low-power density laser welding and high-power density laser welding (Bauerle, 1996). In low-power density laser welding as shown in the Fig. 1, the weld pool is created by melting the material and the fluid flow in the weld pool is driven dominantly by the spatial variation of the surface tension in the weld pool surface caused by the large temperature gradient. The weld pool created by low-power laser welding has no keyhole formation. The width of the weld pool by low-power laser welding is wider than that by high-power laser welding. The depth of the weld pool generated by low-power laser welding is shallower than the one by high-power laser welding. During laser welding processes, the fluid flow and heat transfer in the weld pool significantly affect the width and depth of the weld pool. Studies have shown that the modeling of the laser welding process is very complex since its modeling includes the phenomena such as thermal conduction/convection in phase-change system and fluid flow with free surface effects. There are many previous works (Duley, 1999; Chan et al., 1984; Basu and Debroy, 1992; Kim and Sim, 1997; Robert and Debroy, 2001) dealing with the shape

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Nomenclature

a	coefficient of solution matrix
c_p	specific heat (J/kg K)
$d\sigma/dT$	temperature coefficient of surface tension (N/m K)
δh	grid size (m)
f	volume fraction of material
F_{sa}	surface tension force per unit area (N/m^2)
F_{sv}	surface tension force per unit volume (N/m^3)
g	volume fraction of liquid material
k	thermal conductivity (W/m K)
L	latent heat of fusion (J/kg)
$\vec{n}$	normal vector
p	pressure (Pa)
r	coordinate in radial direction
r_0	radius of laser beam (m)
S	source term
T	temperature (K)
t	time (s)
$\hat{t}$	unit tangential vector
u	velocity (m/s)
$\tilde{u}$	auxiliary velocity computed from incremental changes in u^n (m/s)
z	coordinate in vertical (axial) direction
$[f]$	jump in VOF function

Greeks

α	thermal diffusivity (m^2/s)
κ	curvature of surface (m^{-1})
σ	surface tension (N/m)
μ	dynamic viscosity (kg/m s)

Subscripts

nb	neighboring nodes to node point
p	node point
r	radial direction
s	tangential direction
z	vertical (axial) direction

Superscripts

m	current iteration time level
$m+1$	next iteration time level
n	previous time level
$n+1$	current time level

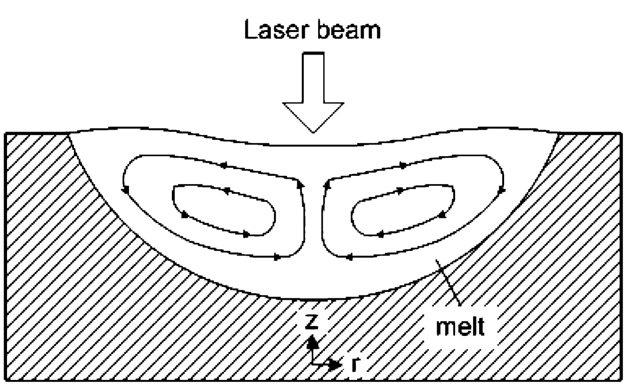

Fig. 1. Schematic representation of the melt pool dynamics in conduction welding.

and size of the weld pool in relation to various laser parameters with non-deformable weld pool surface. Recently, Marathe and Ravi (2004) performed numerical modeling of Marangoni convection with free surface in the Arbitrary Lagrangian Eulerian frame and it was applied laser melting problem. However, the effects of free surface evolution and dimensionless parameters during laser welding have not been extensively examined up to now.

In this study, the free surface evolution is numerically traced by using fixed meshes. The numerical results are validated by comparing the experimental data for laser spot welding on steel (Pitscheneder et al., 1996), gallium (Limmaneevichitr and Kou, 2000) and alumina (Hirsch et al., 1998) plate. The volume-of-fluid (VOF) method (Rider and Kothe, 1998) and modified continuum surface force (CSF) method (Brackbill et al., 1992) are employed in this study to incorporate Marangoni effect with deformable free surface.

2. Numerical model description

2.1. Governing equation

The Eulerian finite difference model considered in this work couples a two-dimensional axisymmetric Navier–Stokes equation solver for fluid flow with free surfaces using RIPPLE (Kothe and Mjolsness, 1991) and energy equation with source-based solidification algorithm (Swaminathan and Voller, 1993). The tracking of free surface is given by the VOF transport equations with piecewise-linear interface calculation (PLIC) method (Rider and Kothe, 1998). The governing equations considered in this study are as follows:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(ru_r) + \frac{\partial}{\partial z}(u_z) = 0 \tag{1}$$